Trans Indian Inst Met (2018) 71(8):1897–1911
https://doi.org/10.1007/s12666-018-1321-0

TECHNICAL PAPER

Mechanical Properties and Tribological Behavior of Al6061–SiC–Gr Self-Lubricating Hybrid Nanocomposites

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Received: 20 November 2017 / Accepted: 4 April 2018 / Published online: 26 April 2018

Abstract In the present investigation, a newly fabricated Al6061 reinforced with various quantity (0.4–1.6 wt%) of nano SiC in steps of 0.4 and fixed quantity (0.5 wt%) of micro graphite particle's hybrid nanocomposites were prepared by ultrasonic assisted stir casting method. The influence of nano SiC and graphite content on the mechanical and tribological properties of Al6061 hybrid nanocomposites were studied. The pin-on-disc equipment was used to carry out experiment at 10–40 N applied load, 0.5 m/s sliding speed and 1000 m sliding distance. The Al/SiC/Gr hybrid nano-composite and matrix alloy wear surfaces were characterized by FESEM equipped with an EDS, 3D profilometer to understand the wear mechanisms. The results of Al/SiC/Gr self-lubricating hybrid nano-composites showed improved wear resistance than the Al6061 matrix alloy. The co-efficient of friction of Al/SiC/Gr hybrid nano-composites were lower than those of the unreinforced alloy at various applied load. Compared to matrix alloy, the surface roughness of Al/SiC/Gr hybrid nano-composites had significantly reduced to 66% at low load and 75% at high load. Self-lubricating Al/SiC/Gr hybrid nanocomposites showed superior surface smoothness compared to matrix alloy.

Keywords Al6061 · Nano-SiC · Graphite · Ultrasonic assisted stir casting · Self-lubricating · Hybrid nanocomposites

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1 Introduction

Today's demand for tough materials in structural, automotive, and aerospace has led to the development of hydrid nanocomposites. The success of the hybrid nanocomposite lies in the selection of matrix and reinforcement particles. Aluminum and its alloy is preferred as matrix over magnesium and titanium alloy. Aluminum alloys find extensive use in designing automotive and aerospace components due to its light weight, strength and stiffness. The use of Aluminum alloys are limited due to their comparatively less wear resistance. To overcome this problem of matrix alloy, aluminum alloys reinforced with ceramic particle and Graphite which possess superior mechanical and tribological properties are used [1]. Among the various reinforcing particles like SiC, Al_2O_3, Si_3N_4, B_4C, MoS_2 and TiC, SiC has proved good compatibility with aluminum alloy resulting in improved wear resistance of the composites. In turn, the reinforcing particles increase the friction between the contact surfaces. To reduce this friction, an appropriate lubricant is added during sliding process. Graphite, a solid lubricant is ideal because it rectifies the disadvantages of liquid lubricants like oil leakage, pollution and high maintenance cost [2, 3].

The Al/SiC/Gr hybrid composites find wide application in advanced engineered materials due to its tribological applications. When the reinforcement particles are of micro size, they improve the strength of the materials, but the ductility of the micro composites weaken when the percentage of reinforcement increases. For less quantity of particulates, the mechanical and tribological properties of nano particle dispersion strengthening the metal matrix composites are far superior to those of their micro particle composites. Aluminum composites reinforced with nano-particles, strengthen the metal matrix and maintain good ductility compared to micro particles [4, 5]. Hence, hybrid composites containing nano-particles can be considered as a new generation of AMCS. A uniform distribution of nanoparticle reinforcement in aluminium alloy, during fabrication of aluminium matrix nanocomposites (AMNCS) is the crucial factor for better mechanical properties of the aluminium matrix nanocomposite. Particles agglomerates or clusters are usually formed in nanocomposites due to various reasons during the manufacturing process [6, 7]. The AMNCS can be prepared by adding nanoparticles into the matrix alloy through powder metallurgy method, disintegrated melt deposition and high intensity ultrasonic stirring. The ultrasonic assisted stir casting method is selected over other methods for its ability in wetting and dispersing nanoparticles in metal matrix [8–11]. The components made from these nanocomposites like piston, inlet and exhaust valve, cylinder liner of internal combustion engine when subjected to sliding movements result in the possibility of large wear damage and huge economic loss causing failure of the component. The reason for the damage and failure of machine parts is friction and wear. Hence the use of self-lubricating hybrid nano-composites improve the wear properties and friction coefficient of nano-composites. The scope of Al/SiC/Gr nano-composites is of great interest for tribological applications in automotive, aerospace industries including engine valves, cylinder liners. The usage of aluminum hybrid self-lubricating nanocomposite components leads to reduce the oil consumption, power loss and maintenance cost.

Ezatpour et al. [12] investigated the effect of 0.4, 0.8 and 1.2 wt% of alumina powder in A7075/Al2O3 nanocomposites and concluded that on adding hard Al2O3 nanoparticles there is an improvement in the strength of the nano composites. Baradeswaran and Elaya Perumal [13] studied the addition of Al2O3 and carbon increased the hardness of the hybrid composites with increasing Al2O3 ceramic particulates. Akhlaghi and Bidaki [14] manufactured AA2024 composites by powder metallurgy method by varying the amount of graphite from 5 to 20% and concluded that the solid Graphite lubricant reduced the hardness, friction coefficient and ultimate strength of composites. Ravindran et al. [15] concluded that the tribological properties of hybrid nano-composites was superior to the matrix alloy. An observation of the above literature survey indicate that it is important to study the mechanical and tribological behavior of Al/SiC/Gr hybrid nano-composites useful in the fabrication of engineering components. The wear behaviour of hybrid AMNCs reinforced with different type of reinforcement has been studied [16–21].

In the present investigation, Al6061 reinforced with nano SiC and graphite particles are fabricated by ultrasonic assisted stir casting method and the effect of nano SiC and graphite on mechanical, friction and wear properties of Al/SiC/Gr hybrid nanocomposites have been studied. Literature review in the field of Al/SiC/Gr hybrid nano-composite shows that no work had been carried out for investigating the tribological and surface roughness of hybrid nanocomposites produced by ultrasonic assisted stir casting method. Hence the present article mainly aims on the study of tribology and wear surface roughness of Al6061 alloy and hybrid Al/SiC/Gr nano-composites by analyzing the worn surfaces by FESEM, EDS, 3D Profilometer.

2 Materials and Methods

The chemical composition (%) of the chosen Al6061 matrix alloy is Mg-0.5, Fe-0.17, Si-0.2, Cu-0.2, Cr-0.3, Ag-0.4 and Al6061 as the remaining balance. Nano-SiC particles supplied by US Research Nano materials, Inc. USA, with an average size of 50 nm and graphite $\leq$ 20 μm supplied by Sigma Aldrich have been used for Nano-composite fabrication.

2.1 Fabrication of Hybrid Metal Matrix Nano-composites

The Fig. 1 shows the ultrasonic cavitation-assisted stir casting system used for the fabrication of AMNC. This Experimental setup had a graphite crucible with a maximum capacity of 1.5 kg and ultrasonic equipment with a working frequency of 20 kHz and 2 KW power output used for melting the alloys. For each batch of trial, 1 kg of Al6061 was initially melted to a temperature of 750 °C in the graphite crucible. In this process, a temperature of about 150 °C above the melting point of alloy was maintained. The inert gas argon was used to protect the melted liquid from the atmosphere. The wettability of SiC nanoparticle of 0.4, 0.8, 1.2, 1.6 wt% (4, 8, 12, 16 g) and graphite 0.5 wt% (5 g) were improved by preheating the particles for 1 h in a muffle furnace. Through a steel tube

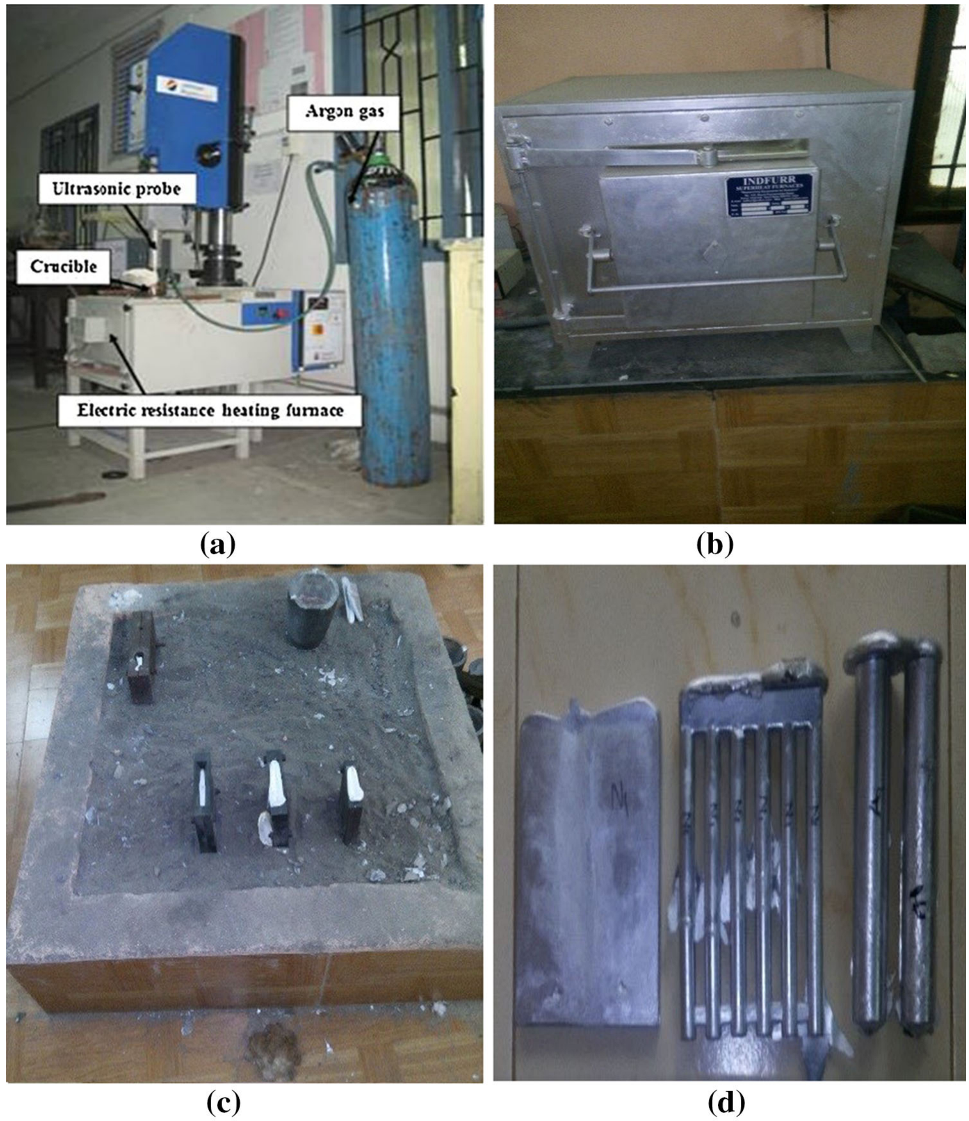


Fig. 1 **a** Experimental setup for fabricating nano-composites, **b** muffle furnace, **c** solidified composites, **d** casted samples

arrangement, the nano sized SiC and graphite particles were fed into matrix melt. When nano SiC particles were injected in the matrix alloy melt, the viscosity of the Al6061 matrix alloy increased. Ultrasonic treatment was done in the melt pool to improve the wettability of the nanoparticles. The furnace melt temperature of 750 °C was maintained to confirm the pouring ability of the alloy melts inside the steel mold. The time maintained for the ultrasound in the fabrication of nanocomposites was 0.4 h to break up the agglomerated and clustered nanoparticles. A steel hardened permanent mold of the casting shape was preheated to 500 °C and the nanocomposite melt was quickly poured into the mold and casted. The Al/SiC/Gr nano-composites was fabricated and for comparison Al6061 matrix alloy was also prepared.

3 Testing and Characterization

3.1 Microstructure Characterization and Mechanical Property Evaluation

The microstructure of the Al/SiC/Gr hybrid nano-composites was characterized by Field Emission Scanning Electron Microscope (ZEISS SIGMAV) and optical microscope. The hardness of the cast nanocomposite samples as per ASTM E384-10 was measured by using the Vickers micro hardness tester. For all the specimens a minimum of six readings were taken by applying a load of 300 g for a period of 30 s.

3.2 Tribological Study, Wear Surface Roughness and Wear Depth Observation

The wear behaviour of the Al/SiC/Gr hybrid nano-composites samples under dry sliding condition were investigated using a pin-on-disc wear test machine (TR-20-PHM-M1 DUCOM), according to ASTM G99 standard. Figure 2 shows the photographic image of pin-on-disc wear test machine during the wear test. The wear tests were performed using cast nanocomposite pins on a hard steel disc of 62HRC under dry sliding condition. The conventional grinding and polishing techniques were used for surface preparation of cylindrical pin and disc surface. The sample of cylindrical pin and disc surface were polished down to 0.15 µm with emery papers of 1000 and 1200 grid size. The applied load for the nano-composite pins were of 10–40 N. The sliding distance 1000 m was employed, with sliding speed of 0.5 m/s. The dimensions of the wear test pins were of diameter 10 mm and height 20 mm. The sliding path on the disc surface was 25 mm diameter. After each test, acetone was used to clean the pin and disc to remove the traces. An electronic balance of 0.1 mg accuracy was used to find the weight of pins. By weighing the pin before and after each wear test, loss of wear of the pin was calculated. The computer system connected with the pin-on-disc wear test machine was used to record the friction co-efficient between the specimen and rotating disc. Surface roughness and depth studies of wear surface of the Al6061 matrix alloy and Al/SiC/Gr hybrid nano-composite samples were carried out by Taylor Hobson 3D Profilometer.

Fig. 2 Photographic image of pin-on-disc wear test machine

4 Results and Discussion

4.1 Microstructure and Hardness of Nanocomposites

Figure 3a–c shows the SEM image of matrix alloy Al6061, nano SiC particles and graphite. The nano SiC particles and micro graphite particles, well distributed within aluminium matrix is found in FESEM image of Fig. 4a–d and optical micrograph image of Fig. 5a–d. The X-ray diffraction patterns of the hybrid nanocomposite samples have been recorded on a Philips PAN analytical X Pert PRO X-ray powder diffractometer. The diffraction angle (2θ) has been maintained between 20° and 80°. Figure 6. Shows the X-ray diffraction (XRD) results of prepared Al/SiC/Gr hybrid nanocomposites. The presence of major peaks indicate aluminium and the minor peaks represent the SiC and Gr particles. The peaks of SiC and Gr in hybrid nanocomposites seem weak because the weight fraction of SiC and Gr is smaller than that of Al. The patterns of XRD show that the SiC and Graphite particles are uniformly distributed in the aluminum matrix [15].

The hardness value of matrix alloy and Al/SiC/Gr hybrid nanocomposite are measured by Vickers micro hardness tester and are listed in Table 1. It is noted from Table 1 that there is a significant increase in hardness of Al/SiC/Gr hybrid nanocomposite sample from 0.4 to 1.6 wt% reinforced SiC with 0.5 wt% Gr particles. The Al/SiC/Gr hybrid nanocomposites offers 38.18, 56.36, 65.45, 63.63% improvement in micro hardness with the addition of 0.4, 0.8, 1.2 and 1.6 wt% SiC nanoparticles with 0.5 wt% Gr. This increase in hardness is due to Orowan strengthening, where the closely packed SiC particles are hard enough to restrict the dislocation of atoms. The increase in the amount of SiC increase the number of obstacles which in turn increase the hardness of the material. There is a significant increase in hardness for 1.2 wt% of SiC compared to matrix alloy. By adding just 0.4–1.6 wt% nano particles in the matrix alloy, the hardness of the nanocomposite increases significantly. This trend has been reported by Sajjadi et al. [5], NarasimhaMurthy et al. [11], and Ezatpour et al. [12]. Addition of graphite leads to decrease in hardness of the hybrid nanocomposite. This is due to variation in thermal expansion of graphite and matrix alloy that arises due to their

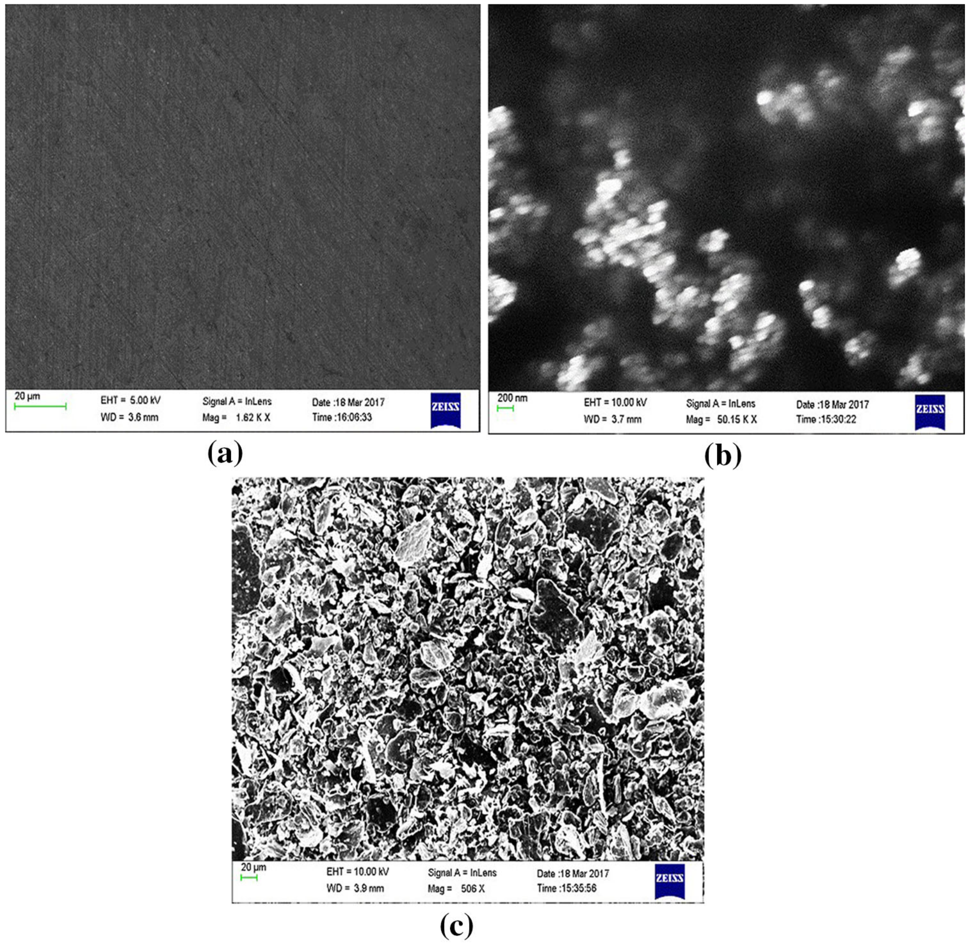


Fig. 3 SEM image of **a** Al6061, **b** nano SiC, **c** micro graphite

nature of bonding. However, the lubrication property of graphite reduces the wear and friction of the hybrid nanocomposite. In Al/SiC/Gr hybrid nanocomposite, the combined effect of hard SiC and soft graphite leads to improved tribological properties.

4.2 Wear Properties

The specific wear rate for matrix alloy and different Al/SiC/Gr hybrid nanocomposite samples plotted against load are shown in Fig. 7. During sliding, the applied load is the key factor affecting the wear of composites. Hosking et al. observed that the wear rates of Aluminum composites reinforced with SiC and Al_2O_3 particle increases by increasing the applied load. Several researchers reported the existence of a critical transition load at which the wear rate increases sharply. In fact when the applied loads are lower than this threshold value, mild or oxidative wear occurs and at higher loads severe or metallic wear accompanied with increased plastic deformation are dominant [4, 18]. From Fig. 7 it is noted that the specific wear rate of Al6061 alloy increases as load is increased from 10 to 40 N. The increase in specific wear rate is due to deterioration of wear at higher load. During sliding wear, there is an increase in temperature of Al6061 alloy resulting in severe damage of surface asperities and decrease the hardness of the material. The hardness of surface sharpness affects the wear resistance of a material as reported by Subramanian [16].

From Fig. 7 it is observed that the specific wear rate of Al/0.4SiC/0.5Gr hybrid nanocomposite is comparatively low as compared to the specific wear rate of Al6061 alloy at all applied load due to increased hardness (Table 1). From the Archards equation

$$V = KWS/3H$$

where V is the volume loss, K is the wear coefficient and represents the wear intensity, S is the sliding distance and H is the hardness. The wear resistance increases with increase in hardness [4]. The improvement in wear resistance against plastic flow decreases the specific wear rate of the hybrid nanocomposites. In Al–SiC–Gr hybrid nanocomposite, the inclusion of hard nano SiC particles improves the hardness and strength and also compensates the weakening effect of graphite. An increase in hardness results in the improvement of wear resistance of materials. Interfacial bond between the

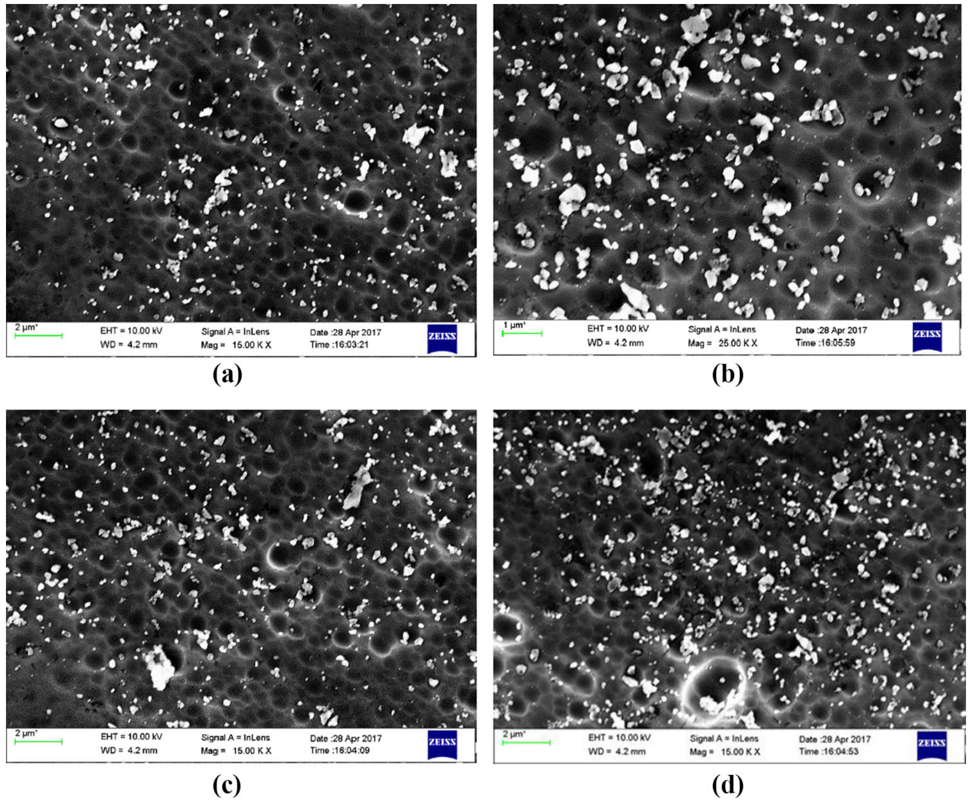


Fig. 4 SEM image of **a** Al/0.4SiC/0.5Gr, **b** Al/0.8SiC/0.5Gr, **c** Al/1.2SiC/0.5Gr, **d** Al/1.6SiC/0.5Gr hybrid nano-composite

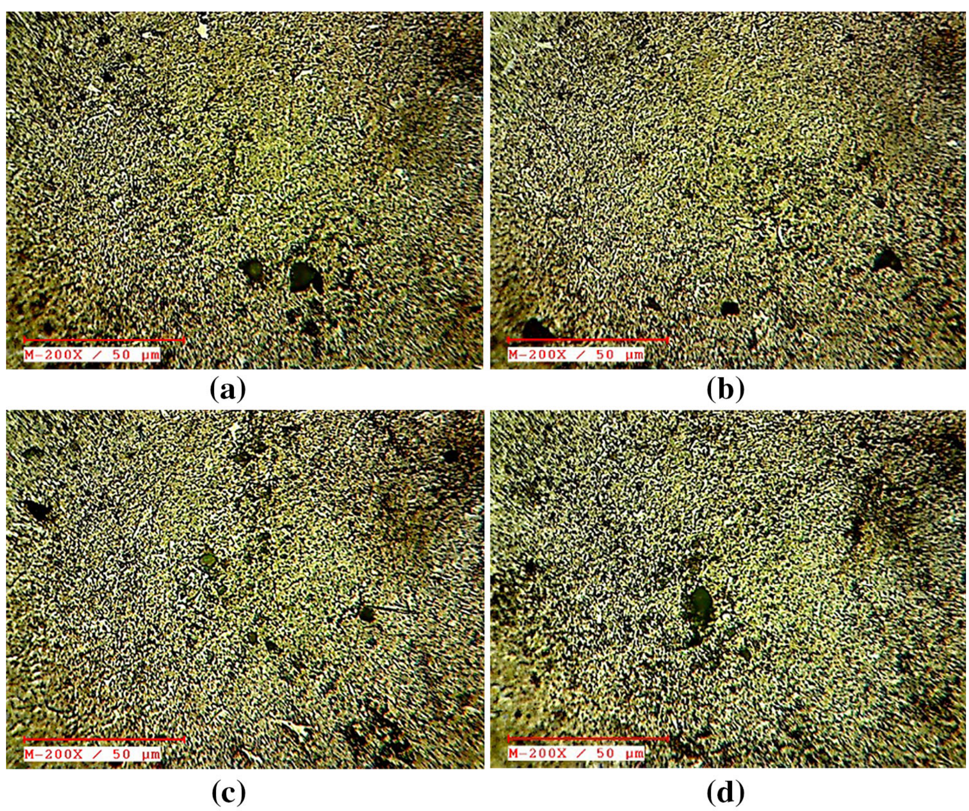


Fig. 5 Optical micrographs of **a** Al/0.4SiC/0.5Gr, **b** Al/0.8SiC/0.5Gr, **c** Al/1.2SiC/0.5Gr, **d** Al/1.6SiC/0.5Gr hybrid nano-composite

matrix alloy and the silicon carbide particles play a major role in wear mechanisms. This outstanding wear resistance of the composites can be attributed to the good interfacial bond between the matrix and the reinforcement. These

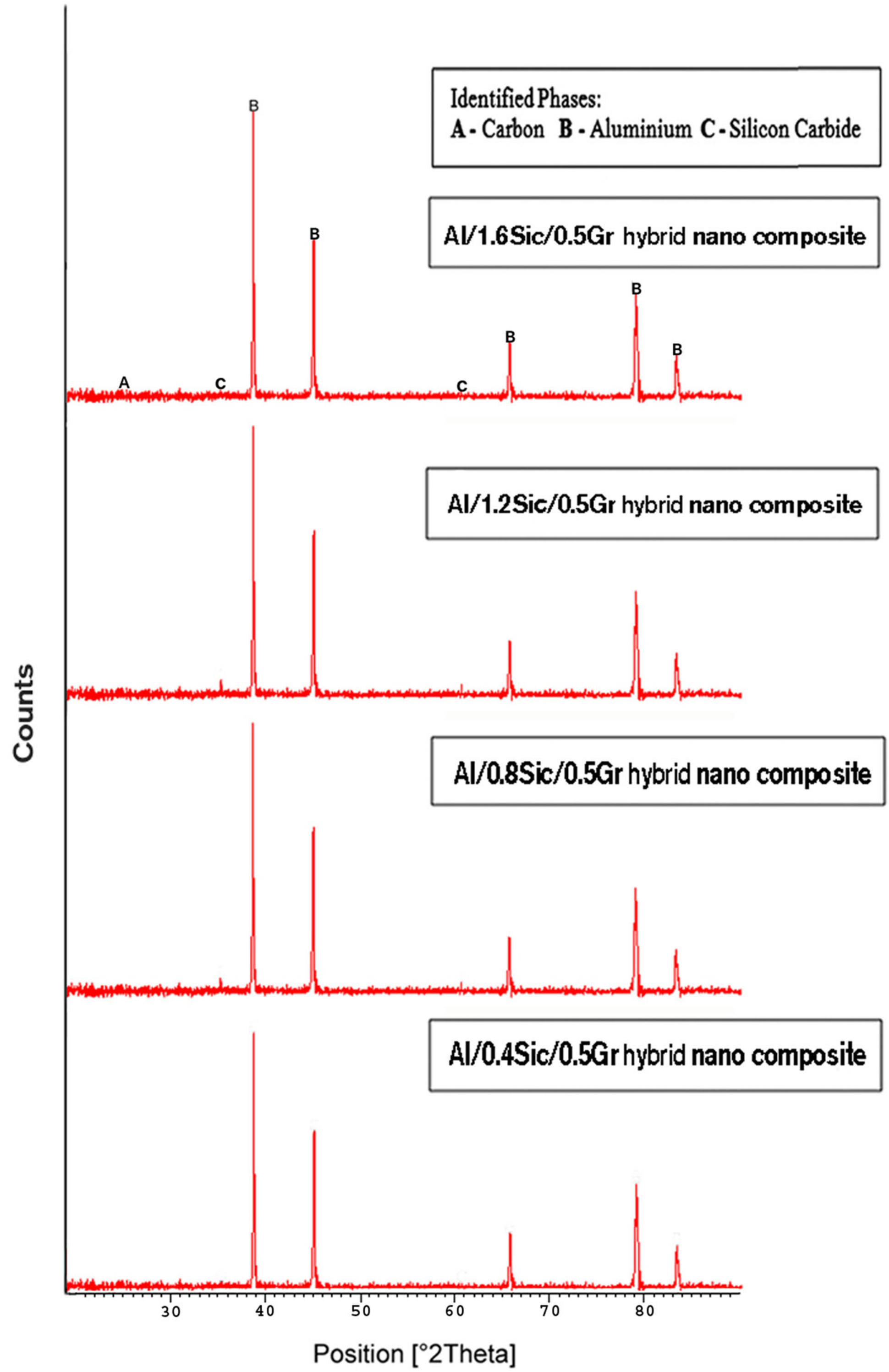


Fig. 6 XRD analysis of **a** Al/0.4SiC/0.5Gr, **b** Al/0.8SiC/0.5Gr, **c** Al/1.2SiC/0.5Gr, **d** Al/1.6SiC/0.5Gr hybrid nanocomposite

nanoparticles also resist the dispersion and cutting of the slider into the surface of the hybrid nanocomposite and thus limiting the delamination. The nano SiC particles acts as load bearing element in the matrix alloy and protect the soft matrix during sliding wear and toughens the Al6061 matrix alloy. Further decrease in wear can be attributed to the lubricating effect of graphite, which prevents the direct contact between pin and disc during sliding wear. However the solid lubricant graphite does not resist the plastic deformation of Al/SiC/Gr hybrid nanocomposite.

From Fig. 7 we have observed that by increasing the percentage of nano SiC from 0.4 to 0.8 wt% in Al/SiC/Gr,

Table 1 Hardness of Al6061 matrix alloy and hybrid nanocomposites

Material	Hardness (VHN)
Al6061	55
Al6061–0.4SiC–0.5Gr	76
Al6061–0.8SiC–0.5Gr	86
Al6061–1.2SiC–0.5Gr	91
Al6061–1.6SiC–0.5Gr	90

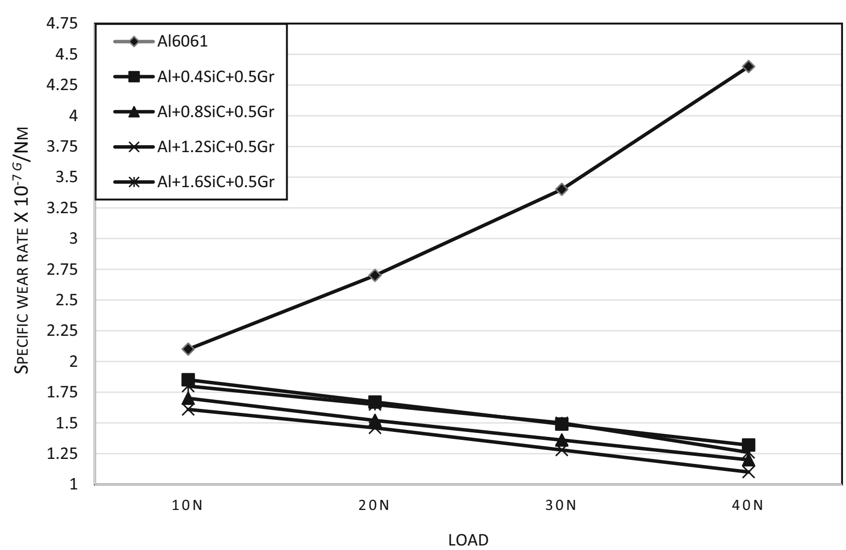
the specific wear rate decreases due to increase in hardness of Al/0.8SiC/0.5Gr than Al/0.4SiC/0.5Gr for all the applied loads. Similar results are obtained for Al/1.2SiC/0.5Gr and it is significantly low compared to other hybrid nanocomposite specimens. On the contrary, when the wt% of SiC is increased from 1.2 to 1.6, the specific wear rate increases. Unlike the other three nanocomposites, the specific wear rate of Al/1.6SiC/0.5Gr does not decrease with increase of load due to agglomeration of hard nano SiC particles. However the wear resistance of Al/1.6SiC/0.5Gr is high compared to matrix alloy. The wear values of Al/0.4SiC/0.5Gr, Al/0.8SiC/0.5Gr, Al/1.2SiC/0.5Gr, Al/1.6SiC/0.5Gr are 0.0054, 0.0049, 0.0047, and 0.0050 g respectively. These trends are consistent with the results of Mosleh-shirazi and Akhlaghi [20].

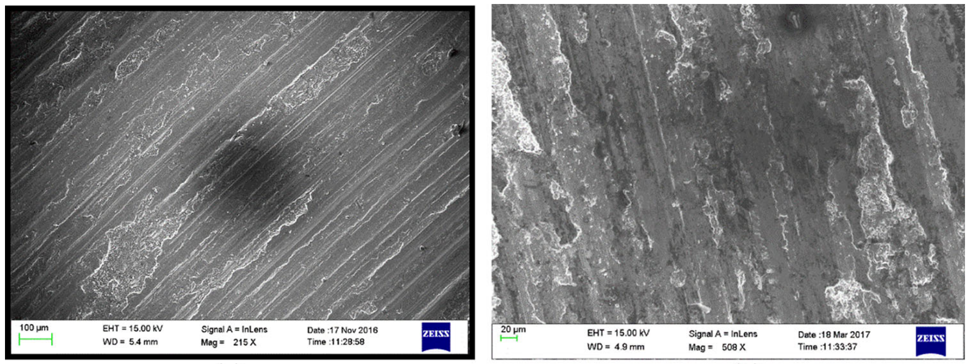
4.3 Wear Surface Analysis

During dry sliding wear, appreciated information on the mechanism of wear is noted and it is clearly seen in the wear surface SEM image. Figure 8a presents the worn surface of Al6061 matrix alloy pin tested by applied load of 10 N. It is noted that the furrows and some scratches are seen parallel to the sliding direction, indicating the abrasive wear. Figure 8b indicates worn surface of Al6061 at 40 N load. At high load, the abrasive wear decreases and an increase in adhesive wear creates deep holes resulting in big size wear debris. From the hardness Table 1 and specific wear rate graph Fig. 7, we can find that the hardness enhancement and wear resistance of Al/1.2SiC/0.5Gr is significantly high compared to Al/1.6SiC/0.5Gr hybrid nanocomposite. So we have analysed the worn surface of Al/1.2SiC/0.5Gr hybrid nanocomposite for tribological applications [4]. The worn surface of Al/1.2SiC/0.5Gr hybrid nano-composite tested at the applied load of 10 N is shown in Fig. 9a.It shows parallel and shallow grooves which is an indication of abrasive wear. It is noted from Fig. 9b that the shallow craters indicate that abrasive wear is less effective for the applied load of 40 N. Compared to the worn surface of Al6061 matrix alloy, the alloy deformation on the worn surface of Al/1.2SiC/0.5Gr hybrid nano-composite is very small.

The worn surface of the hybrid nano-composites exhibit finer grooves and small plastic deformation at the edges of the grooves. The surface also appears smooth because of the graphite reinforcement content. The graphite is released to the wear surface during the sliding wear. The worn surface of Al/1.2SiC/0.5Gr hybrid nano-composite is characterized by small plastic deformation and a clear evidence of smearing results in least amount of wear loss. From the SEM image shown in Fig. 9a, b, different wear mechanisms can also be clearly observed. The wear surface of Al/SiC/Gr hybrid nano composite is covered with graphite (black film) and the grooves are mostly restricted. The worn surfaces of the hybrid nanocomposites are filled with lubricating layer. The wear size in the worn surface is smaller because of the presence of graphite self-lubrication. It can be recognized that the graphite rich lubricating layer at the sliding surface plays an important role in the wear

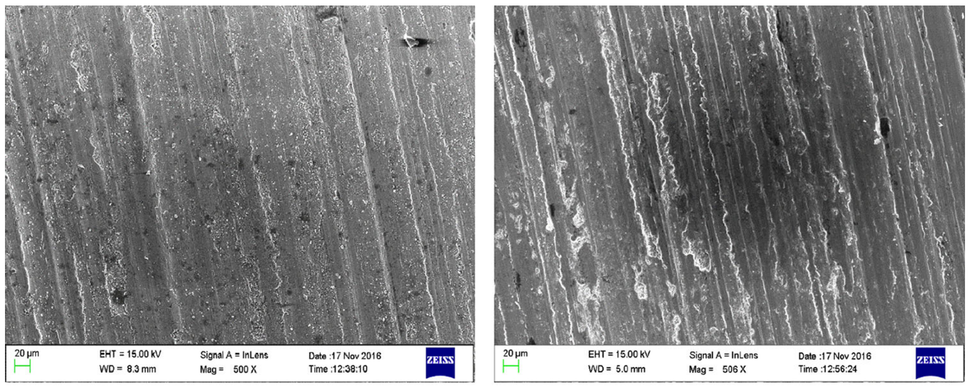
Fig. 7 Specific wear rates of hybrid nano-composite samples at different applied load





(a) (b)

Fig. 8 SEM micrographs of surface of Al6061 pins worn under load of **a** 10 Nand **b** 40 N



(a) (b)

Fig. 9 SEM micrographs of the worn surface of Al/1.2SiC/0.5Gr hybrid nano-composite. **a** 10 N, **b** 40 N

behavior of hybrid nano-composites. The lubricating layer is formed as a result of shearing of graphite particles positioned immediately below the contact surface and most of the worn surface is covered uniformly by the graphite lubricating film which can prevent direct contact between the pin and the counter face. Consequently, the possibility of abrasive wear in the Al/SiC/Gr hybrid nano-composites is low; delamination and oxidative wear are the dominant wear mechanisms [15]. The graphite particle present in the Al/1.2SiC/0.5Gr hybrid nanocomposite act as a solid lubricant and delay the changeover from mild to severe wear. This self-lubricating property of graphite improves the tribological properties of hybrid aluminium metal matrix nanocomposites [22–26].

Figures 10a, b and 11a, b show the cross sectional SEM micrographs and EDS analysis of a worn surface of Al6061 alloy and Al/1.2SiC/0.5Gr hybrid nano-composite, after the wear test under 40 N load. The cross sectional worn surface EDS analysis of Al6061 pin shown in Fig. 11a tested at the applied load of 40 N majorly contains aluminium indicating that the wear mechanism has no considerable change in the composition of the wear surface, which shows that the base alloy wear is more compared to the disc surface. When compared to the Al/1.2SiC/0.5Gr hybrid nano-composite worn surface, the plastic deformation of the Al6061 matrix alloy is more. The plastic deformation and wear of Al6061 matrix alloy is high compared to disc surface, since the hardness of the disc is high. In the morphological examinations of the worn surface of matrix alloy, abrasive and adhesive wear mechanisms are dominating [4].

During sliding movement, the mechanically mixed layer (MML) formed due to the oxidation of wear debris of the hybrid nanocomposite remain on the worn surface forming a protective layer. Comparing the cross sectional SEM micrographs of worn surface of Al6061 alloy and Al/1.2SiC/0.5Gr hybrid nano-composite, the presence of MML is confirmed. The presence of MML layer is consistent with earlier studies by Mohammad Sharif et al. [22]. By comparing the EDS analysis of hybrid nanocomposite and Al6061 matrix alloy, it is observed from Fig. 11b that a high amount of iron and oxygen exist on the hybrid nanocomposite surface. The hybrid nanocomposite worn surface has a hard layer consisting of a combination of aluminium, iron and their oxides and hence the abrasive wear damage is low compared to the Al6061. When the applied load is increased from 10 to 40 N, the surface temperature of the hybrid nanocomposite increases leading to the formation of oxygen in large quantity on the worn surface. The hard MML layer present in the Al/1.2SiC/0.5Gr hybrid nano-composite effectively reduces the wear rate of hybrid nanocomposite compared to matrix alloy.

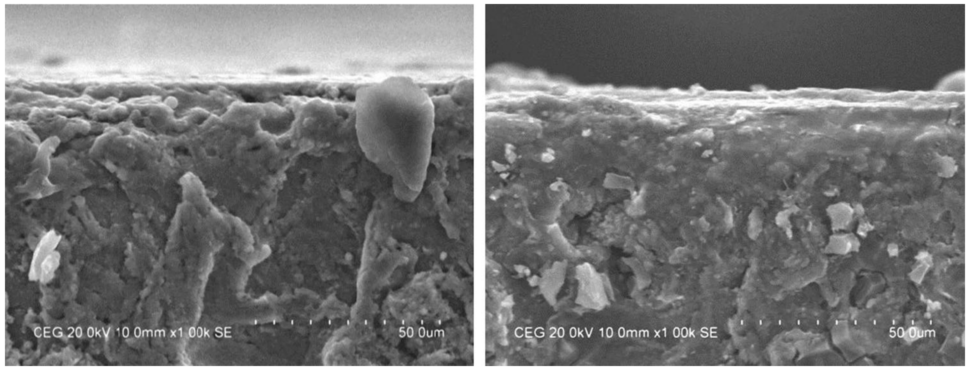


Fig. 10 Cross-sectional SEM micrographs of the wear track of **a** Al6061, **b** Al/1.2SiC/0.5Gr hybrid nano-composite

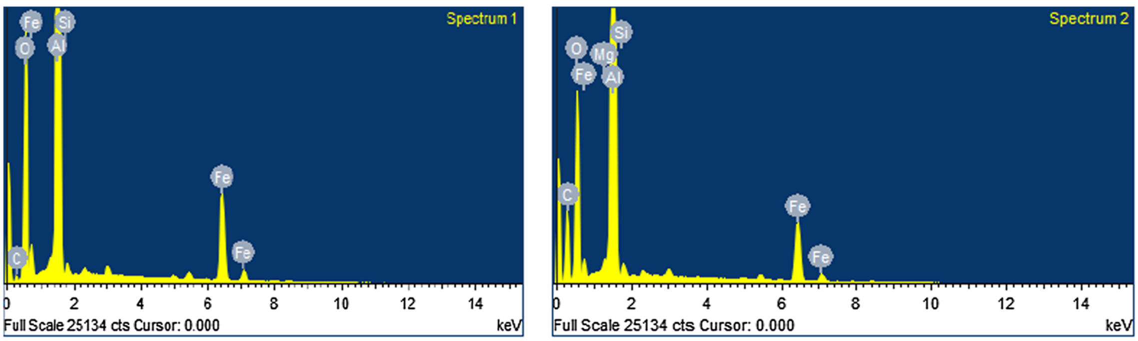
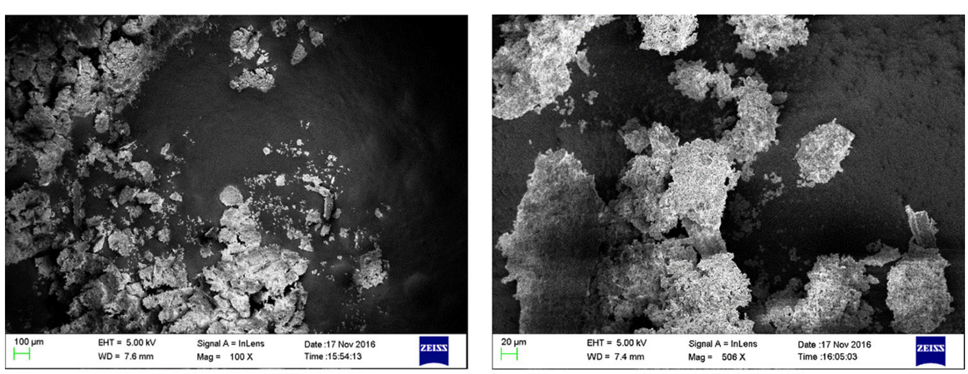


Fig. 11 EDS result of Cross-sectional SEM micrographs of the wear track of **a** Al6061, **b** Al/1.2SiC/0.5Gr hybrid nano-composite

4.4 Wear Debris

Figure 12a presents SEM image of Al6061 wear debris generated at the applied load of 40 N. The large weight loss and the appearance of big size wear debris is attributed to adhesive wear process of Al6061 matrix alloy. Severe plastic deformation caused by dislocation in the contact region under compression and shearing is due to the combined action of adhesion and sliding. Material in the softer asperity deforms in a series of shear bands. When each shear band touches a certain limit, a crack is initiated or an existing crack propagates until a new shear band is formed. When the crack reaches the contact interface, a wear particle is formed and adhesive transfer is completed. The big size wear debris of matrix alloy is formed due to this mechanism.

The SEM image of debris particles collected after the wear test of Al/1.2SiC/0.5Gr hybrid nano-composite at 40 N load under dry sliding contact is shown in Fig. 12b. It indicates thin sheets and very fine irregular shaped powder morphologies indicating that delamination is the main wear mechanism in these hybrid nanocomposites. Delamination is caused by inhomogeneous plastic deformation at the reinforcement–matrix interfaces, which results in dislocation's accumulation, stress concentration, crack formation, and propagation at the interface. These cracks join together and make flaky wear debris.The wear debris of Al/1.2SiC/0.5Gr hybrid nano-composite samples is very small in size



(a) (b)

Fig. 12 **a** SEM micrographs of Al6061 wear debris particle at a load of 40 N, **b** wear debris particles of Al/1.2SiC/0.5Gr hybrid nano-composite under a load of 40 N compared to the debris of Al6061 matrix alloy. The graphite particles scattered in the aluminium matrix minimize the mean size of the wear particle. The morphology and size of the wear debris of Al/SiC/Gr hybrid nano composite is decided by the graphite in the hybrid nanocomposite [15, 20, 26].

4.5 Coefficient of Friction

Figure 13 shows the variation of Coefficient of friction (COF) plotted against applied load for the matrix alloy and different hybrid nanocomposites. It is observed that coefficient of friction (COF) of Al6061 matrix alloy increases drastically on increasing the applied load from 10 to 40 N due to increased frictional force. This increase in COF can be attributed to the fact that increase in load on the pin holder causes the surface asperities to penetrate deep into the wearing surface. It can be observed from Fig. 13 that the COF of hybrid nanocomposites having various SiC reinforcement wt% and with 0.5 wt% Gr are lower than Al alloy for all applied loads. The COF of hybrid nanocomposites is not greatly affected by applied load as in Al6061 alloy. This difference is due to the wear behavior of hybrid nanocomposites and the lubricating property of graphite. The formation of MML layer and increased hardness of hybrid nanocomposites decreases the plastic deformation at the contact surface which in turn leads to the decrease in COF.

The effect of the wt% of SiC in Al/SiC/Gr hybrid nanocomposites as seen in Fig. 13 clearly depicts that the COF is decreased when wt% of SiC is increased from 0.4 to 1.6 insteps of 0.4. The COF values of different wt% of SiC and with 0.5Gr for different load shows only slight variation. The Al/1.2SiC/0.5Gr shows the least COF compared to other hybrid nanocomposite samples due to its improved wear characteristics. The decrease in COF is due to the fact that the hard SiC nanoparticles enhance the hardness resulting in improved wear resistance, less plastic deformation and reduced wear debris formation. The nano SiC particle decreases the contact area between pin and disc which results in decreased frictional force between contact surfaces and hence COF is decreased. The graphite forms a thin self-lubricating layer at the contact surface which reduces adhesion at the wear surface and leads to significant decrease in COF compared to matrix alloy. Similar findings have been reported by Mahdavi and Akhlaghi [20, 25].

4.6 Wear Surface Roughness

Figure 14a shows the 3D topography of Al6061 matrix alloy with 10 N load. It shows the shallow ploughing grooves with no deep craters. Figure 14b represent the 3D topography of Al6061 matrix alloy at 40 N load in which severely damaged surface with deep grooves and craters are noted. The effect of applied load on the surface of the matrix alloy, increases the coefficient of friction and plastic flow, which in turn increase the surface roughness. Figure 15a indicates 3D topography of Al/1.2SiC/0.5Gr hybrid nano-composite worn surface, which reveals the shallow grooves at 10 N load. Figure 15b represents the worn surface of Al/1.2SiC/0.5Gr hybrid nano-composite with 40 N load. It shows slightly deep grooves and scratches in the surface. It also reveals that the surface is less rough when compared to Al6061 matrix alloy. It is observed that the worn surface of Al6061 matrix alloy have big peaks and deep valleys. Small peaks and shallow

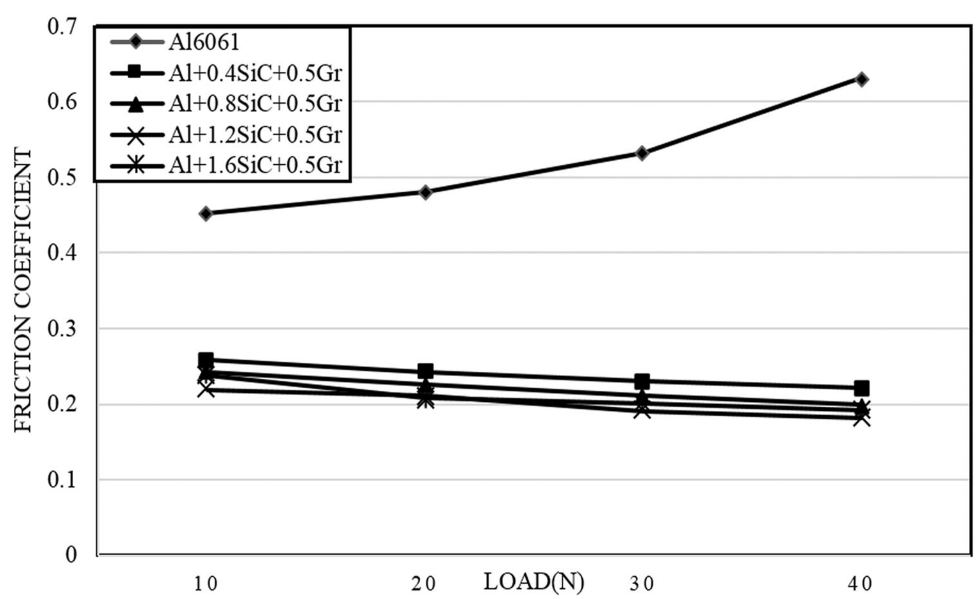


Fig. 13 Coefficient of friction for Al6061 alloy and different hybrid nano-composite

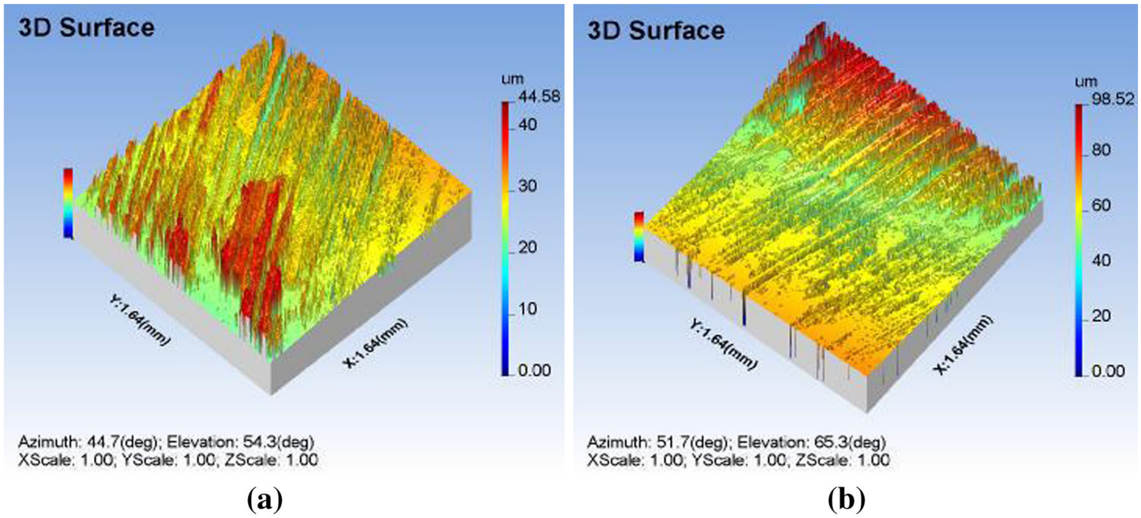


Fig. 14 Three dimensional worn surface roughness plot of Al6061 alloy **a** 10 N and **b** 40 N

valleys are noticed in Al/1.2SiC/0.5Gr hybrid nano-composite worn surface. The addition of nano SiC to the matrix alloy decreases the surface roughness. The SiC reinforcement decreases the deformation level which obstructs the plastic flow of the matrix during wearing process. During dry sliding of Al/SiC/Gr hybrid nanocomposite, a thin lubricant layer is formed on the tribo-interface due to the fracture of carbon particles at contact surfaces. The solid lubricant film resist the plastic flow in the tribo-interface region and prevent direct pin to disc contact surface, which improves the tribology and surface smoothness of hybrid nano-composites [26–28].

The Fig. 16a indicates the wear track generated on the Al6061 matrix alloy at 10 N load. It reveals that the surface is affects with respect to the input parameters and attains surface roughness value of 1.99 µm. Figure 16b represent the wear track generated on the Al6061 alloy at 40 N load. It is observed that the surface roughness of Al6061 alloy at 40 N load is 6.20 µm. It is noticed from Fig. 17a, b that the surface roughness of Al/1.2SiC/0.5Gr at 10 and 40 N load is 0.67 and 1.56 µm. The surface roughness values of other hybrid nanocomposite combinations are shown in Table 2. The reduction of surface roughness for Al/1.2SiC/0.5Gr hybrid nanocomposite compared to matrix alloy is 66% at low load. The reduction of surface roughness for Al/1.2SiC/0.5Gr hybrid nanocomposite compared to matrix alloy is 75% at high load. The width and depth of the wear grooves of the hybrid nanocomposite worn surface are reduced. The numbers of grooves are less in the hybrid nano-composite compared to Al6061 matrix alloy. Similar reports have also been reported by Kaushik and Rao [29]. The hybrid nanocomposites with self-lubricating property

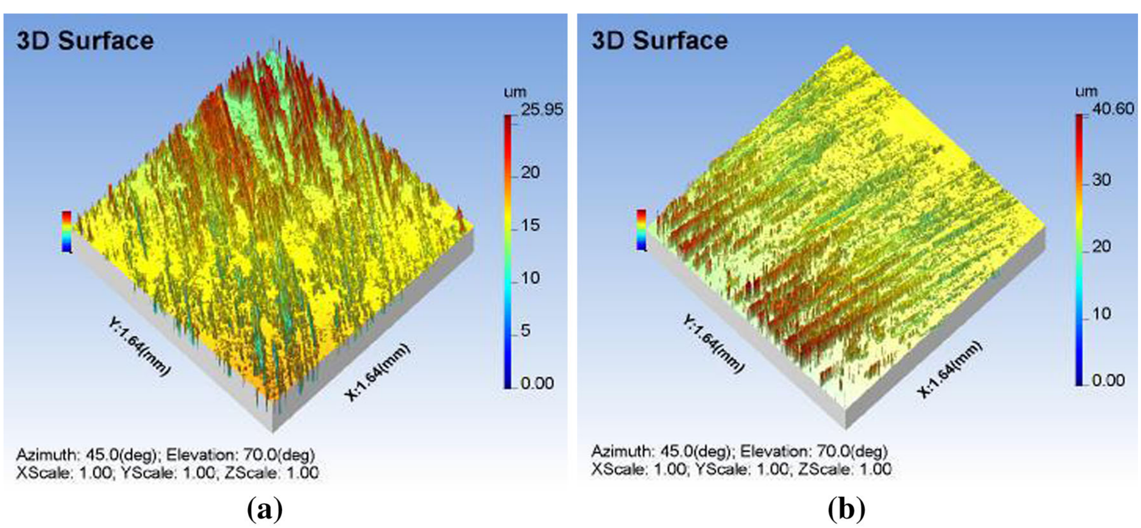


Fig. 15 Three dimensional worn surface roughness plot of Al/1.2SiC/0.5Gr hybrid nano-composite **a** 10 N, **b** 40 N

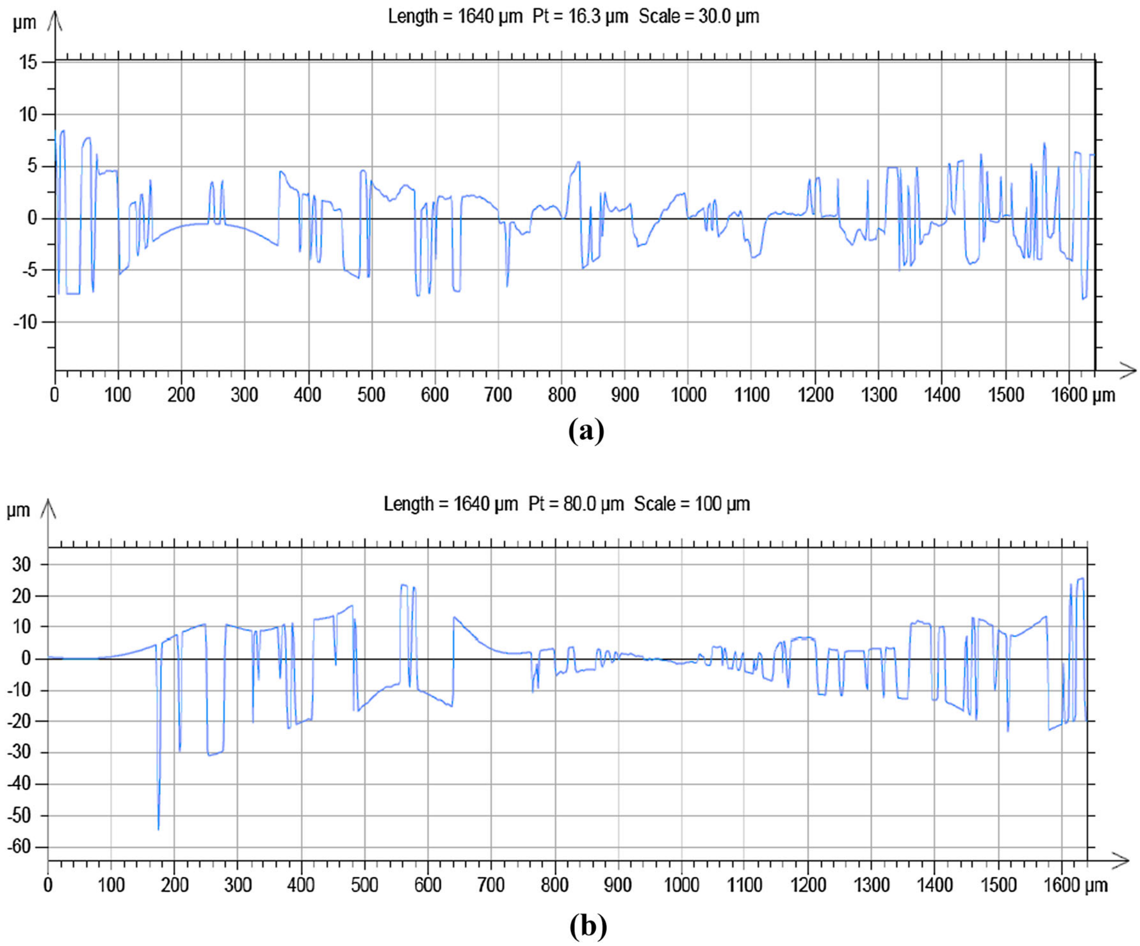


Fig. 16 Two dimensional roughness graph of Al6061 alloy **a** 10 N, **b** 40 N

significantly reduces the surface roughness of the hybrid nano composite compared to the matrix alloy. The hard SiC nano particles increases the hardness of the hybrid nanocomposite which enables to bear the load and hinder the deformation of the surface of Al/SiC/Gr by preventing the matrix against extensive wear during sliding. The soft graphite particles create a solid lubrication film between contact surfaces which decreases the friction coefficient, wear rate and reduce further deformation of the surface. The hybrid nanocomposite shows surface smoothness after dry sliding wear. This property is expected in engineering components subjected to wear which finds applications in automotive and aerospace industries [30–32].

5 Conclusions

In this research work, Aluminum matrix reinforced with nano-SiC and micro-graphite was synthesized by ultrasonic assisted stir casting method and the tribological behavior of these hybrid nanocomposites was investigated. The experimental noting's are summarized as follows:

- The soft matrix alloy is protected by the hard SiC nano particle which obstruct the dislocation movement.
- The Al/1.2SiC/0.5Gr hybrid nano-composite have enhanced mechanical and tribological properties compared to matrix alloy.
- The Al/1.2SiC/0.5Gr hybrid nano-composite have less co-efficient of friction than that of the matrix alloy at all applied load and reach a minimum of 0.23 at 40 N load.
- The Al/1.2SiC/0.5Gr hybrid nano-composite worn surfaces indicate grooves of shallow depth when compared to unreinforced matrix alloy.
- The wear surface roughness of Al/1.2SiC/0.5Gr hybrid nano-composite is significantly reduced to 1.56 µm compared to Al alloy roughness of 6.2 µm at 40 N load.
- The reduction of surface roughness of Al/1.2SiC/0.5Gr hybrid nanocomposite compared to matrix alloy is 66% at low load. The reduction of surface roughness of Al/

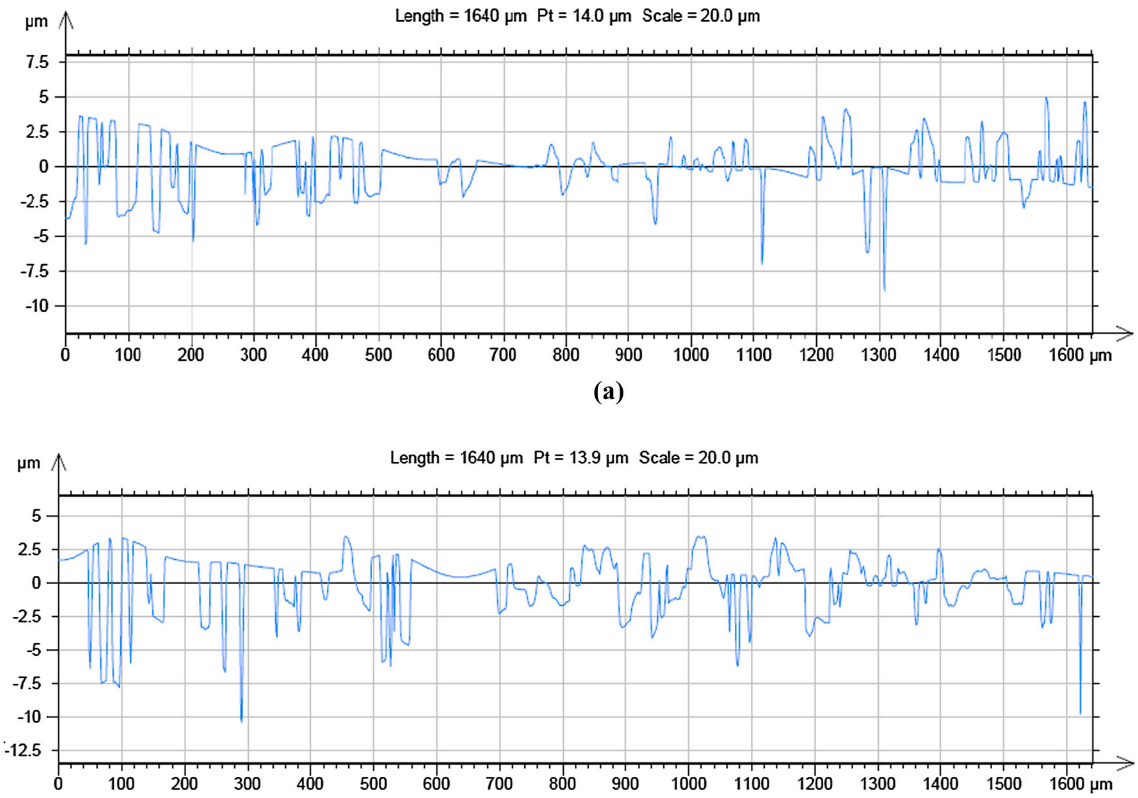


Fig. 17 Two Dimensional roughness graph of Al/1.2SiC/0.5Gr hybrid nano-composite **a** 10 N, **b** 40 N

Table 2 Surface roughness of matrix alloy and hybrid nanocomposites

Load	Surface roughness, Ra (µm)				
	Al6061	Al6061–0.4SiC–0.5Gr	Al6061–0.8SiC–0.5Gr	Al6061–1.2SiC–0.5Gr	Al6061–1.6SiC–0.5Gr
40 N	6.2	1.78	1.68	1.56	1.65

1.2SiC/0.5Gr hybrid nanocomposite compared to matrix alloy is 75% at high load.

- Self-lubricating Al/1.2SiC/0.5Gr hybrid nanocomposite shows superior surface smoothness compared to matrix alloy.

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